SOME ELEMENTARY THEORETICAL CONSIDERATIONS OF THE RELATIONSHIPS BETWEEN WIND AND PRESSURE IN LOW LATITUDES

STANLEY L. ROSENTHAL AND ROBERT W. REEVES

National Hurricane Research Laboratory, Environmental Science Services Administration, Miami, Fla.

ABSTRACT

The relationship between wind and pressure in the equatorial zone of a barotropic, nondivergent atmosphere is examined. Cyclostrophic effects prove to be of major importance. The results indicate that it is extremely difficult to devise pictorial models of the wind-pressure relationship near the equator. The impact of this conclusion upon operational low-latitude analysis by both subjective and machine methods is discussed.

1. INTRODUCTION

Low-latitude analysis of the field of motion is difficult because the data are sparse and frequently of poor quality. Some advocate direct analysis of the wind reports with little or no weight to be placed upon pressure observations [5]. Others [3], however, feel that construction of a reasonable pressure pattern is the most useful approach to establishing the field of motion in low latitudes. In the latter case, it is necessary to have models which allow the pressure pattern to be converted to a picture of the wind field. In either case, however, not all of the available information is used. The problem of wind-pressure relationships is, therefore, of direct practical significance. It is also one of long-standing theoretical interest.

Scale analysis [2] indicates that adiabatic, inviscid, synoptic-scale motions near the equator should be very nearly nondivergent (in fact, more so than in middle latitudes). Similar conclusions are reached from linear analysis of the primitive equations [6]. Latent heat released in regions of organized convection and radiative effects due to the presence of clouds are probably the only large diabatic effects on disturbances in the equatorial zone. Hence, synoptic disturbances not associated with significant convection should be expected to have small divergence, which then implies the validity of the balance equation (above the friction layer). Further explorations of the dynamics of nondivergent flow in the equatorial zone would, therefore, seem to be in order.

The approach adopted is similar to that previously employed by Sellick [8]. However, because of his use of spherical coordinates, Sellick's [8] work is somewhat difficult to follow. Furthermore, Sellick's approximations appear to be very nearly equivalent to a beta-plane assumption (although this is well hidden in the spherical coordinate notation). Also, inconsistencies appear in his work. For example, his meridional flow (his equation (3)) is proportional to sin $b\varphi$ where b is a constant and φ is the latitude. Yet his figures (his figures 1a, 1b, 1c) show non-zero meridional motion at the equator.

In the following, we re-examine Sellick's problem. The mathematics are greatly simplified through the a priori introduction of the beta-plane. Also, we go somewhat beyond Sellick in interpreting the solutions.

2. THEORETICAL ASPECTS

The governing equations for horizontal, nondivergent, barotropic flow in the p-system referred to an equatorially oriented beta-plane may be written

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-\beta yv+\frac{\partial\phi}{\partial x}=0, \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\beta yu+\frac{\partial\phi}{\partial y}=0, \tag{2}$$

$$u=-\frac{\partial\psi}{\partial y}, \tag{3}$$

$$v=\frac{\partial\psi}{\partial x} \tag{4}$$

where x is zonal distance (positive eastward), y is meridional distance (positive northward), u is the zonal component of the wind (positive eastward), v is the meridional component of the wind (positive northward), t is time, ϕ is the geopotential of isobaric surfaces, $\beta=\partial f/\partial y$ (f is the Coriolis parameter) is constant, and ψ is the stream function. By cross-differentiation of (1) and (2), we obtain the barotropic vorticity equation

$$\frac{\partial\zeta}{\partial t}-\frac{\partial\psi}{\partial y}\frac{\partial\zeta}{\partial x}+\frac{\partial\psi}{\partial x}\frac{\partial\zeta}{\partial y}+\beta\frac{\partial\psi}{\partial x}=0, \tag{5}$$

where

$$\zeta=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}=\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}. \tag{6}$$

It is well known that (5) has solutions of the form

$$\psi=-Uy+[\psi_s \sin my+\psi_c \cos my] \sin k(x-ct) \tag{7}$$

provided that the wave speed, c, is given by the Rossby-Haurwitz relationship,

$$c=U-\frac{\beta}{k^2+m^2} \tag{8}$$

In (6), (7), and (8), U is a constant zonal current, ψ_s and ψ_c are constant amplitude factors, k and m are, respectively, zonal and meridional wave numbers. When $\psi_s=0$, the circulation will be called symmetric; when $\psi_c=0$, the circulation will be called asymmetric.

By use of (1), (2), (3), (4), (7), and (8), the distribution of z is obtained.

$$\begin{aligned} z=\frac{\phi}{g}=&\frac{\beta m}{g(k^2+m^2)} [\psi_s \cos my-\psi_c \sin my] \sin k(x-ct) \\ &+\frac{\beta}{g} y[\psi_s \sin my+\psi_c \cos my] \sin k(x-ct) \\ &-\frac{m^2}{2g} (\psi_s^2+\psi_c^2) \sin^2 k(x-ct) \\ &-\frac{k^2}{2g} [\psi_s \sin my+\psi_c \cos my]^2-\frac{\beta y^2 U}{2g}. \end{aligned} \tag{9}$$

3. DISCUSSION

Case 1.—If we choose $\psi_s=0$ (symmetric case), $m=k=\pi\times10^{-6}$m.$^{-1}$ (wavelengths of 2000 km.), $k\psi_c=5$ m. sec.$^{-1}$, we obtain results similar to those shown by Sellick's figures (1a) and (1b) depending upon whether we choose $U=\beta/(k^2+m^2)$ or $U=0$. The former choice leads, of course, to a stationary wave. The latter gives a wave which moves westward at 1.16 m. sec.$^{-1}$

We will examine the $U=0$ case. The flow pattern as shown by the stream function (fig. 1a) indicates alternating cells of clockwise and counterclockwise circulation centered on the equator. Figure 1c shows the contribution to the isobaric height pattern from the linear terms (first two terms on the right-hand side) of equation (9). This is the height field needed to balance the linear part of the inertial terms and the Coriolis terms. The amplitude of this pattern is extremely small; central values differ from the mean for the surface by only 0.25 m. or so. Clearly, streamlines and contours do not line up in the usual geostrophic sense.

Figure 1d shows the contribution to the height field of the nonlinear (inertial) terms (third and fourth terms on right-hand side) of equation (9). We note that the amplitude is about an order of magnitude greater than that of the linear terms. These nonlinear terms represent curvature effects and, as inspection of equation (9) shows, their relative importance will decrease as the scale of motion increases (decreasing m and k) and increase in importance as the disturbances become more intense (increasing ψ_c). The height pattern produced by the nonlinear terms is one of Lows centered on the equator at the centers of circulation. Between the Lows, Highs are centered at $y=\pm500$ km. The association of low centers with the circulation centers is to be expected since the contribution of the nonlinear terms to the pressure field is cyclostrophic in nature. This also explains why the high cells shown by figure 1d are associated with saddle points in the stream field.

The total height field (fig. 1b) is very much like that produced by the nonlinear terms alone. The shifting of the low centers from the equator is a Coriolis effect; a clockwise circulation centered on the equator will always tend to be associated with high pressure north of the equator and low pressure to its south. This is clear from inspection of the second term of equation (9). The opposite is true of counterclockwise circulations centered on the equator.

The clockwise cell of figure 1a is anticyclonic in the Northern Hemisphere and cyclonic in the Southern Hemisphere. In both hemispheres it is seen to be associated with low pressure. Hence, in the Northern Hemisphere, we have anticyclonic flow about a Low; in the Southern Hemisphere, we have the normal case of cyclonic flow about a Low. The reverse is true of the counterclockwise cell shown by figure 1a.

For reference purposes the absolute vorticity (ζ_a) is shown by figure 2. Positive ζ_a corresponds to counterclockwise turning (cyclonic vorticity in the Northern Hemisphere and anticyclonic vorticity in the Southern Hemisphere). The reverse is true of negative ζ_a.

In the case in which $U=1.16$ m. sec.$^{-1}$ (for which $c=0$), the results are much the same as those just shown.

Case 1b.—We examine next the patterns produced by superimposing a basic easterly current on the perturbations. If we choose $U=-3.84$ m. sec.$^{-1}$ then the wave speed will be -5 m. sec.$^{-1}$, $\psi_s=0$, $m=k=\pi\times10^{-6}$ m.$^{-1}$, and $k\psi_c=5$ m. sec.$^{-1}$ This corresponds to Sellick's figure 1c.

The flow pattern (fig. 3a) is distinctly wave-form with circulation centers between 200 and 300 km. from the equator. The linear and nonlinear height fields are identical to those of Case 1 (figs. 1c and 1d). The total height field (fig. 3b) is obtained by adding $-(\beta y^2U/2g)$ to figure 1b.

The circulation center corresponding to the Northern Hemispheric Low is situated well south of the equator. The flow north of the equator follows the contours reasonably well. South of the equator, the streamlines and contours cross at relatively large angles. The converse is true for the Southern Hemispheric Low.

Some further considerations of the stream and height patterns (figs. 3a and 3b) are of interest. The normal component of the equation for horizontal motion may be written,

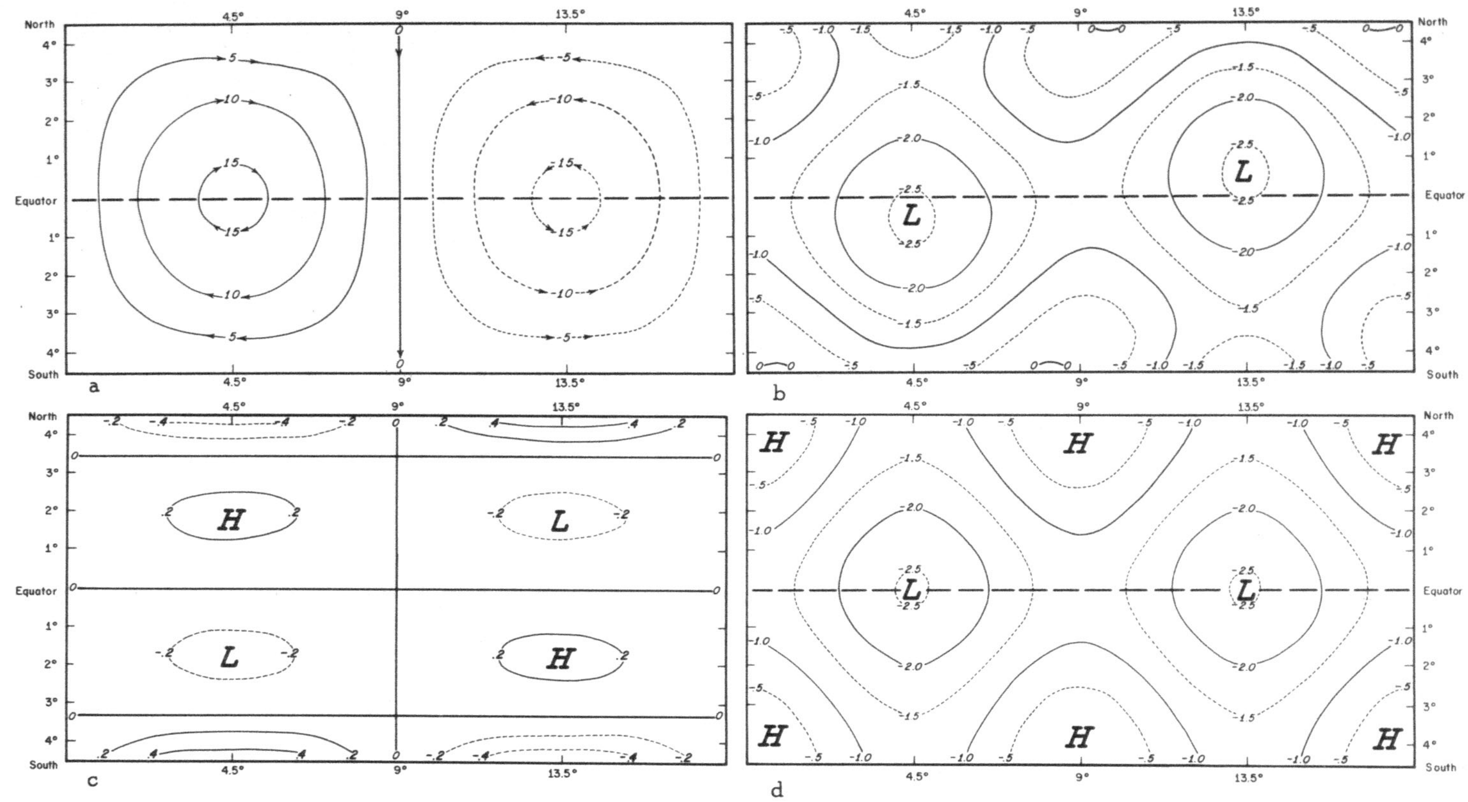


FIGURE 1.—Case 1. $\psi_s=0$, meridional and zonal wavelengths=2000 km., $k\psi_c=5$ m. sec.$^{-1}$, and $U=0$ ($c=-1.16$ m. sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed from equation (7). Isopleths are labeled in units of 10^5m.^{2} sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters. (c) Isobaric height pattern from the linear inertial and Coriolis terms of equation (9). Isopleths are labeled in meters. (d) Isobaric height patterns from the nonlinear inertial terms of equation (9). Isopleths are labeled in meters.

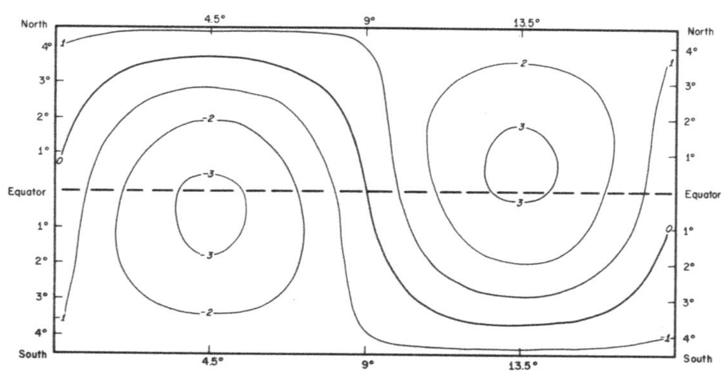
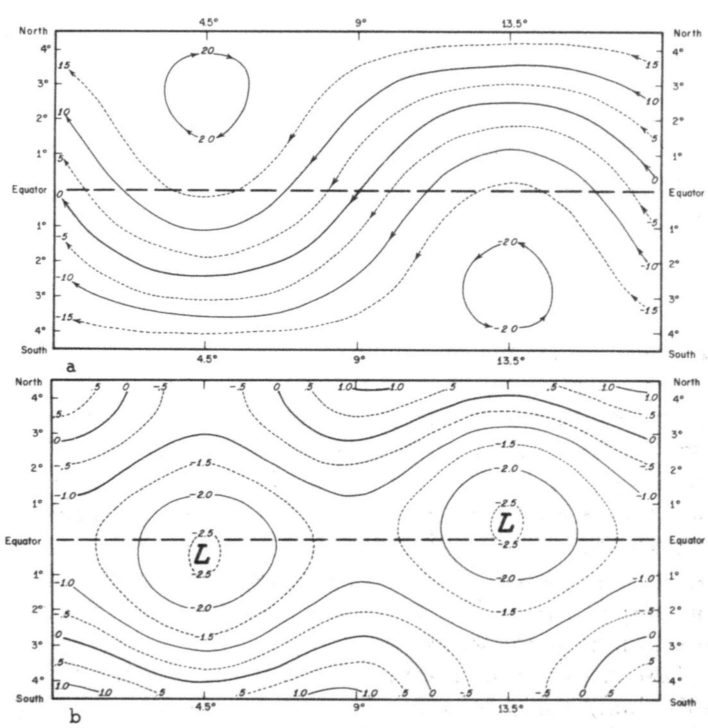


FIGURE 2.—Absolute vorticity for Cases 1 and 1b (obtained by adding f to equation (6)). Isopleths are labeled in units of 10^{-5} sec.$^{-1}$.

FIGURE 3.—Case 1b. $\psi_s=0$, meridional and zonal wavelengths 2000 km., $k\psi_c=5$ m. sec.$^{-1}$, and $U=-3.84$ m. sec.$^{-1}$ ($c=-5$ m. sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed from equation (7). Isopleths are labeled in units of 10^5 m.^{2} sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters.



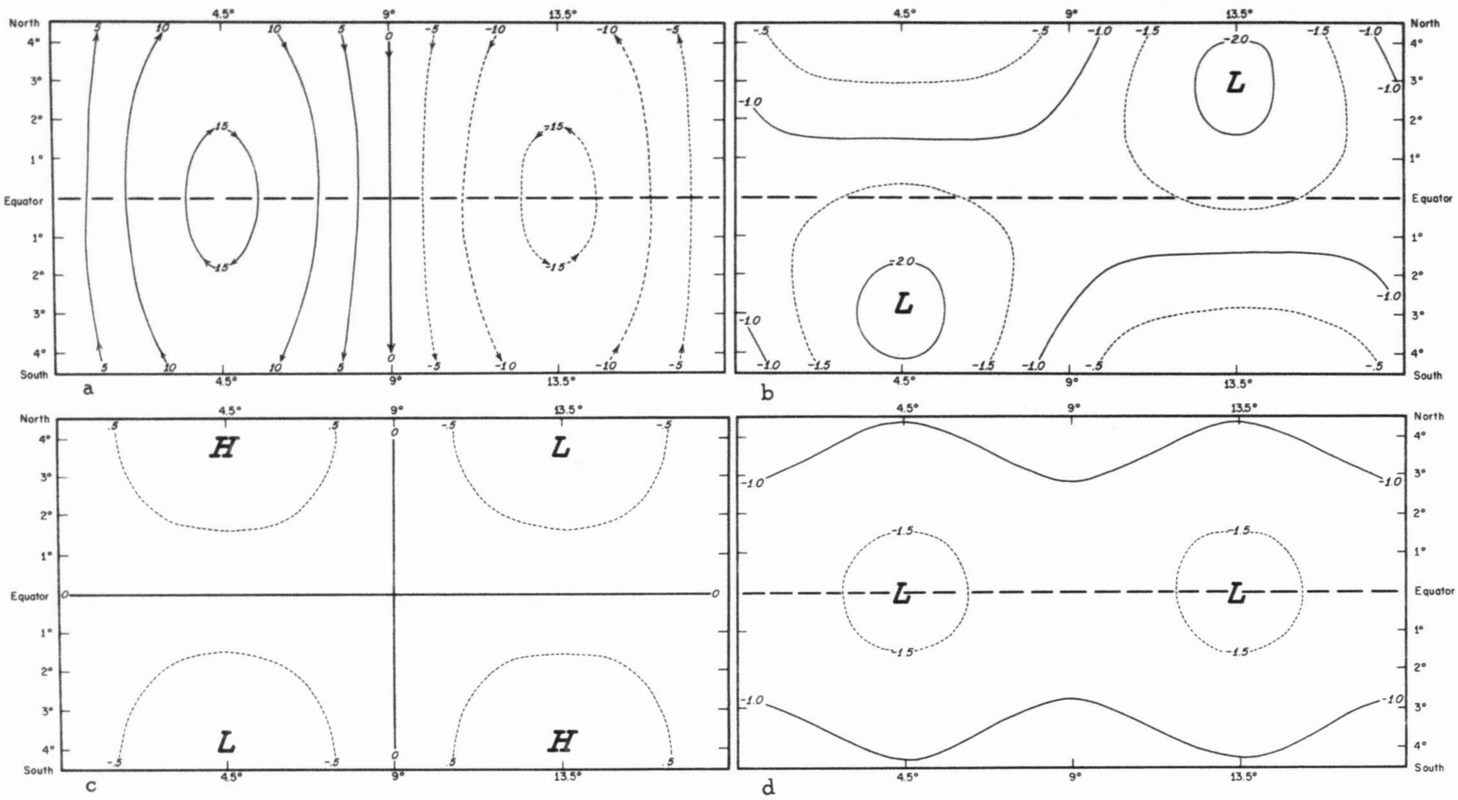


FIGURE 4.—Case 2. $\psi_s=0$, meridional wavelength=4000 km., and zonal wavelength=2000 km., $k\psi_c=5$ m. sec.$^{-1}$, and $U=0$ ($c=-1.86$ m sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed from equation (7). Isopleths are labeled in units of 10^5 m.^{2} sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters. (c) Isobaric height pattern from the linear inertial and Coriolis terms of equation (9). Isopleths are labeled in meters. (d) Isobaric height pattern from the nonlinear inertial terms of equation (9). Isopleths are labeled in meters.

$$KV^2+fV+\frac{\partial\phi}{\partial n}=0, \tag{10}$$

where V is the wind speed, K is the trajectory curvature (positive for counterclockwise turning) and n is the distance normal to the streamlines (positive to the left of the motion). At the equator,

$$KV^2=-\frac{\partial\phi}{\partial n}. \tag{11}$$

We select a point on the equator at the crest of the stream pattern wave (fig. 3a) with counterclockwise turning. Here, the pressure gradient force is directed northward (see fig. 3b), giving a positive $\partial\phi/\partial n$. From equation (11), the trajectory curvature at this point must be clockwise (a southward centrifugal force). This may be verified by examination of the absolute vorticity pattern (fig. 2) (since ζ_a is conserved, the ζ_a isopleths must coincide with the trajectories). The trajectory curvature is then opposite to that of the streamline.

Case 2.—Upon doubling the meridional wavelength (to 4000 km.) while holding all other parameters constant ($\psi_s=0$, $k=\pi\times10^{-6}$ m.$^{-1}$, $m=(\pi/2)\times10^{-6}$ m.$^{-1}$, $k\psi_c=5$ m.

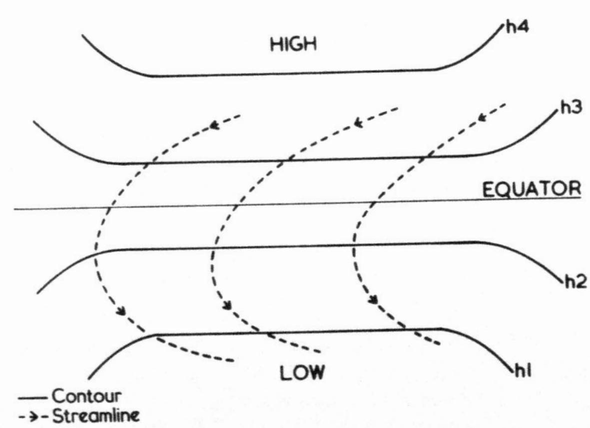


FIGURE 5.—Schematic representation of the "Equatorial Drift" (after Johnson and Mörth [4]). Contours are solid lines, streamlines are dashed.

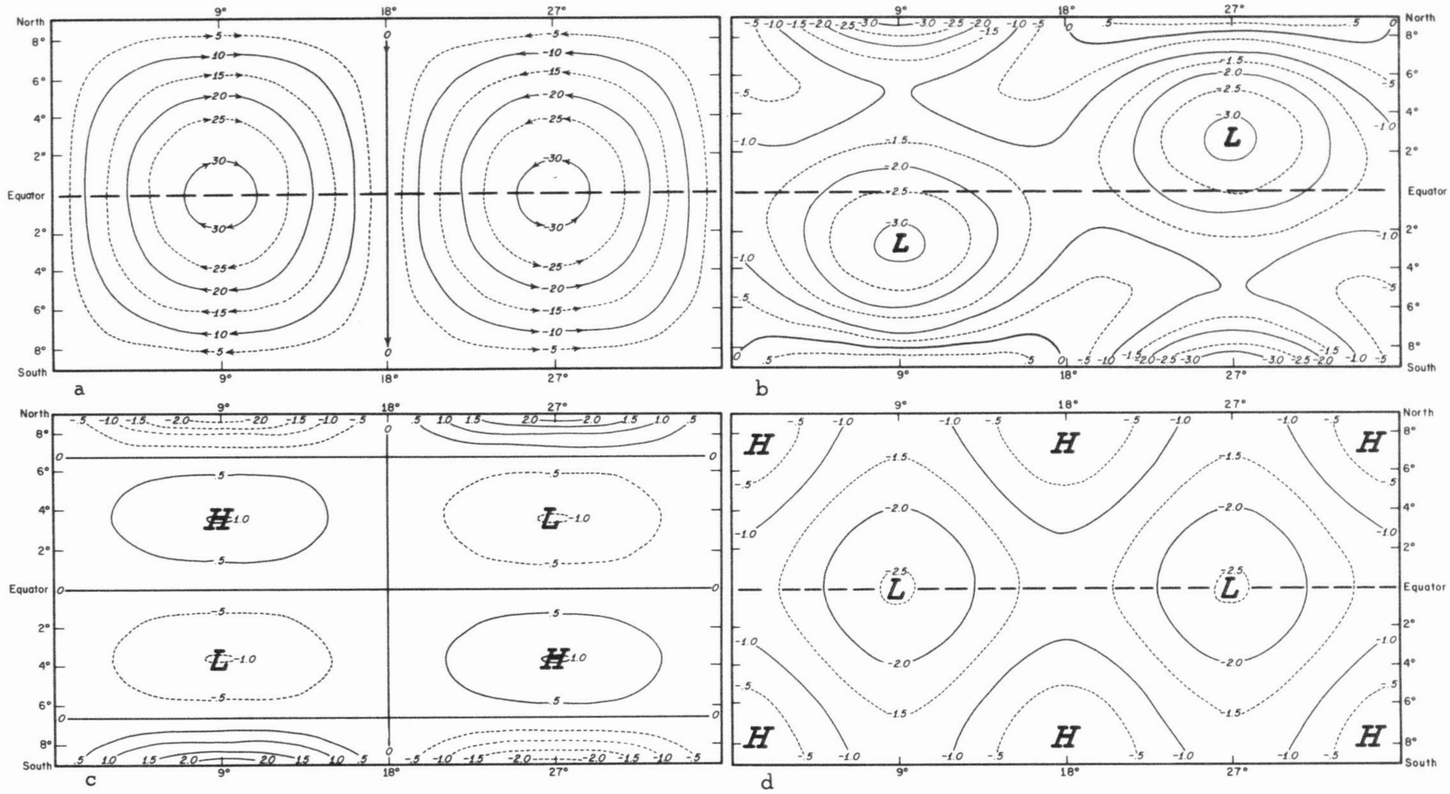


FIGURE 6.—Case 3. $\psi_s=0$, the meridional and zonal wavelengths=4000 km., $k\psi_c=5$ m. sec.$^{-1}$, and $U=0$ ($c=-4.65$ m. sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed from equation (7). Isopleths are labeled in units of 10^5 m.^{2} sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters. (c) Isobaric height pattern from the linear inertial and Coriolis terms of equation (9). Isopleths are labeled in meters. (d) Isobaric height pattern from the nonlinear inertial terms of equation (9). Isopleths are labeled in meters.

sec.$^{-1}$, and $U=0$, $c=1.86$ m. sec.$^{-1}$), we obtain the flow pattern shown by figure 4a. The pattern again consists of alternating clockwise and counterclockwise cells centered on the equator. The cells are, however, more elongated in the north-south direction than are those of Case 1. If the contributions to the height field from the linear and nonlinear terms (figs. 4c and 4d) are compared, the importance of the nonlinear terms is again demonstrated. The gradients of the linear contribution (fig. 4c) are weak but central values now differ from the mean for the surface by approximately 1 m. The importance of the nonlinear (fig. 4d) terms has diminished somewhat in comparison with Case 1.

The low centers of the total height field (fig. 4b) are in this case displaced about 300 km. from the equator. Note that Southern Hemispheric Lows are paired with Highs north of the equator at the same longitude and vice versa. This pressure pattern is similar to that called the "drift" by Johnson and Mörth [4]. The "drift" and the associated wind field postulated by Johnson and Mörth are shown by figure 5.

Our results show a similar flow pattern only on the eastern sides of the Northern Hemispheric Highs. On the western sides we find the flow to be in the reverse sense of that postulated by Johnson and Mörth.

Adding a basic zonal current of $U=1.16$ m. sec.$^{-1}$ renders the patterns stationary. The results are much the same as those just discussed.

Case 3.—In this case, the meridional and zonal wavelengths are both 4000 km. The scale of motion is then twice that of Case 1. $\psi_s=0$, $m=k=(\pi/2)\times10^{-6}$ m.$^{-1}$, and $k\psi_c=5$ m. sec.$^{-1}$ The flow pattern with $U=0$ ($c=-4.65$ m. sec.$^{-1}$) is shown by figure 6a and, except for scale, is similar to that of Case 1. The height field (fig. 6b) displays some similarity to the height field of the first case (fig. 1b). The Lows are somewhat deeper and displaced approximately 300 km. from the equator. The order of magnitude of the linear height terms is 1 m. in figure 6c. The contribution to the height field by the nonlinear terms (fig. 6d) is of the same order as that of the linear terms. Contours and streamlines are not oriented in the usual geostrophic sense.

Case 4.—We set $\psi_c=0.0$ and choose $k\psi_s=5$ m. sec.$^{-1}$ (asymmetric case). $k=m=\pi\times10^{-6}$ m.$^{-1}$ (zonal and meridional wavelengths of 2000 km.). The stream pattern with $U=0$ (wave speed $c=-1.16$ m. sec.$^{-1}$) is shown by

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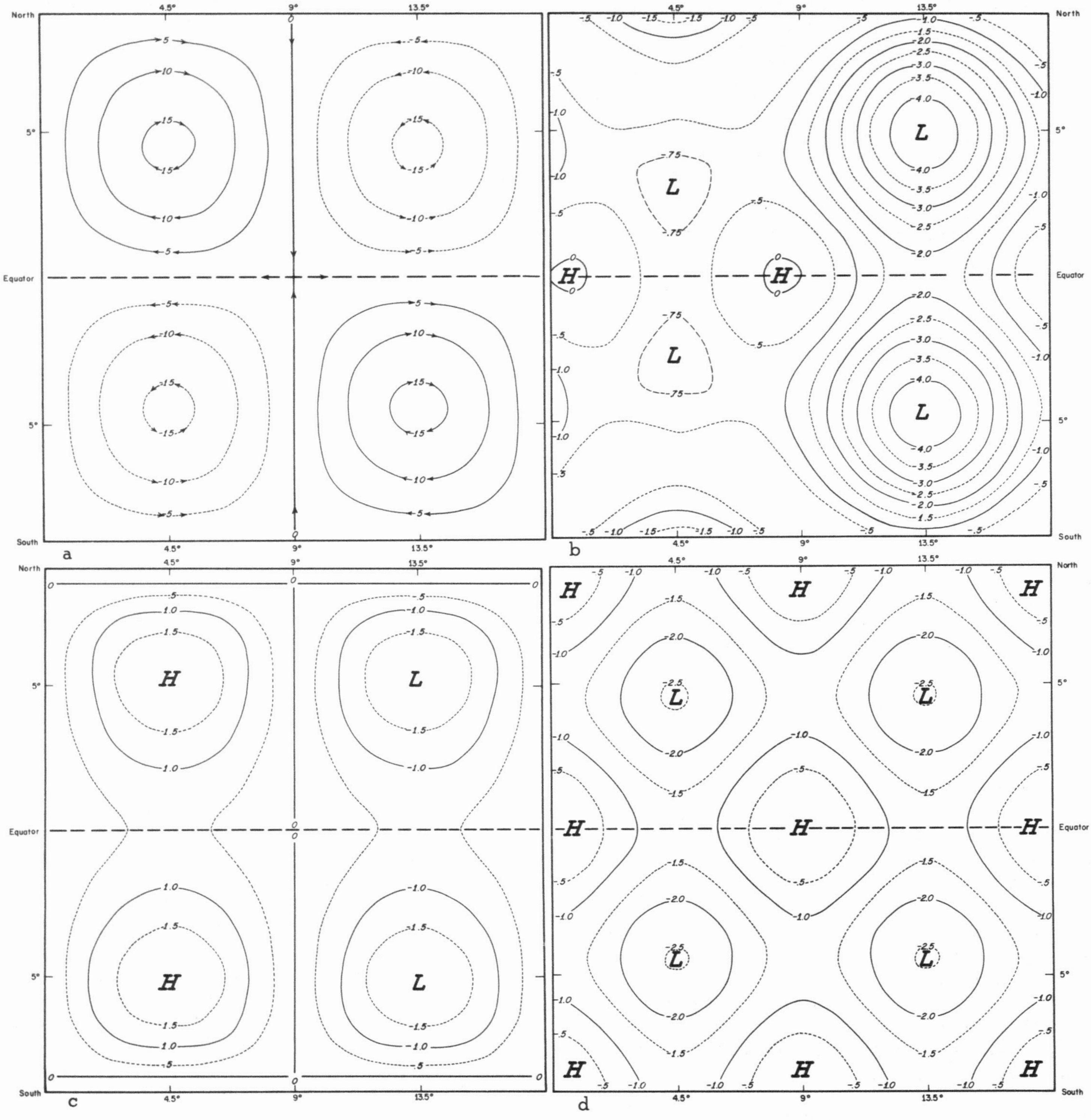

FIGURE 7.—Case 4. $\psi_c=0$, $k\psi_s=5$ m. sec.$^{-1}$, zonal and meridional wavelengths=2000 km., and $U=0$ ($c=-1.16$ m. sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed from equation (7). Isopleths are labeled in units of 10^5 m.^{2}sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters. (c) Isobaric height pattern from the linear inertial and Coriolis terms of equation (9). Isopleths are labeled in meters. (d) Isobaric height pattern from the nonlinear inertial terms of equation (9). Isopleths are labeled in meters.

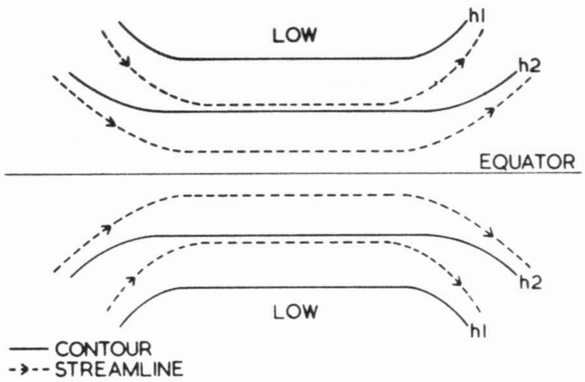

FIGURE 8.—Schematic representation of the "Equatorial Bridge" (after Johnson and Mörth [4]). Contours are solid lines, streamlines are dashed.

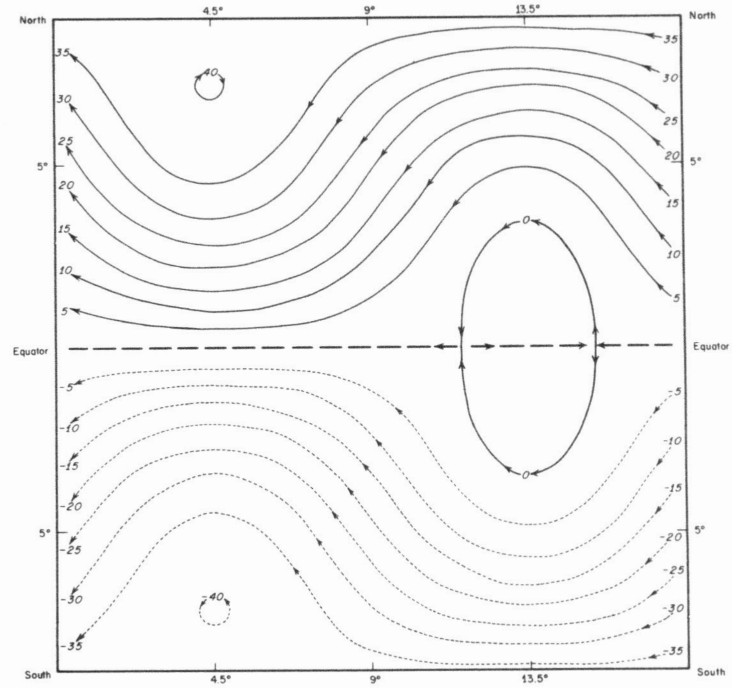

FIGURE 9.—Case 4 with $U=-3.84$ m. sec.$^{-1}$ ($c=-5$ m. sec.$^{-1}$). Stream function computed from equation (7). Isopleths are labeled in units of 10^5 m.^{2} sec.$^{-1}$

figure 7a and indicates cells of alternating clockwise and counterclockwise circulation centered 500 km. from the equator. The height field is shown by figure 7b. The height patterns associated with the cyclonic circulations are well-defined Lows. In the vicinity of the anticyclonic circulations, however, the height field is quite flat. The height pattern in the eastern portion of figure 7b is similar to the "equatorial bridge" (fig. 8) described by Johnson and Mörth [4]. These authors postulate westerly flow near the equator to accompany the "bridge" pressure pattern. Our results are in agreement with this.

The height contribution to figure 7b made by the linear terms (fig. 7c) is similar to what we might expect from geostrophic reasoning. Examination of the contribution produced by the nonlinear terms (fig. 7d) shows a series of Lows centered on the circulation centers as would be expected from cyclostrophic reasoning. Cyclostrophic Highs (fig. 7d) are associated with neutral points in the wind field. Unlike the symmetric case of the same scale (Case 1), the nonlinear and linear contributions are of the same order of magnitude.

The Lows in the eastern part of figure 7b are associated in the classical manner with cyclonic circulation; the linear terms and cyclostrophic terms of equation (9) are of the same sense. The total height field (fig. 7b) shows Highs centered on the equator which are associated cyclostrophically with saddle points in the wind field. This is contrary to Brunt's [1] statement to the effect that closed Highs are not possible as stable systems near the equator unless the wind blows directly across the isobars and not around them. The small patches of low pressure in the western part of figure 7b are due to cyclostrophic dominance in a region where linear effects counteract cyclostrophic effects. These are associated with anticyclonic absolute vorticity and are centered equatorward of the circulation centers of the anticyclones in each hemisphere.

Adding a basic easterly flow of $U=-3.84$ m. sec.$^{-1}$ (wave speed of -5 m. sec.$^{-1}$) produces the stream pattern shown by figure 9 but changes the height pattern (fig. 7b) very little. This points out the difficulty of devising pictorial wind-pressure relationships for low latitudes. The flow patterns of figures 7a and 9 are associated with more or less the same pressure pattern.

Case 5.—We take meridional and zonal wavelengths of 4000 km. and retain the values used in Case 4 for the remaining parameters ($\psi_c=0.0$, $k\psi_s=5$ m. sec.$^{-1}$, and $k=m=(\pi/2)\times10^{-6}$ m.$^{-1}$). The flow pattern with $U=0$ ($c=-4.65$ m. sec.$^{-1}$) is shown by figure 10a. The corresponding height field (fig. 10b) shows Highs centered on the same meridian as, and approximately 200 km. poleward of, the anticyclonic circulation centers. The low centers more nearly coincide with the cyclonic circulation centers than do the high centers with the anticyclonic circulation centers. The stronger association of Highs with anticyclonic flow in comparison with Cases 1–4 indicates the increased importance of the linear effects for Case 5. This is verified by examination of figures 10c and 10d. The linear terms (fig. 10c) are larger than the nonlinear terms (fig. 10d) but not by as much as one order of magnitude. For this case, the height and stream patterns bear a closer resemblance to that expected from geostrophic reasoning. The stream and pressure patterns strongly resemble those of Johnson and Mörth's [4] "diamond" pattern (fig. 11). However, our contours east of the col in the wind field are convex toward the low pressure areas rather than toward the Highs.

The western part of the patterns of figures 10a and 10b resemble the "duct" of Johnson and Mörth [4], where Highs straddling the equator are associated with easterly

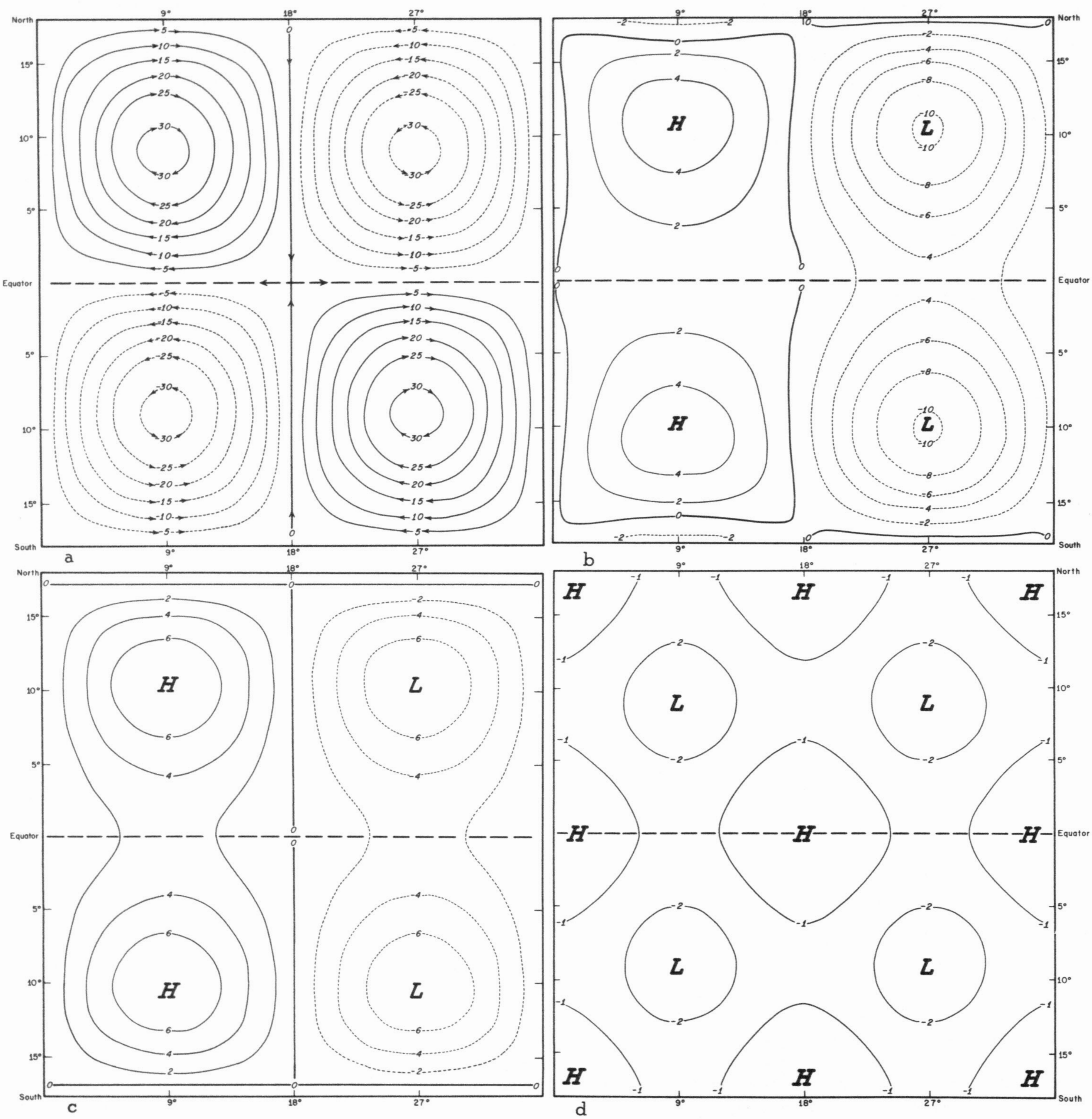

FIGURE 10.—Case 5. $\psi_c=0$, $k\psi_s=5$ m. sec.$^{-1}$, and zonal and meridional wavelengths equal to 4000 km. $U=0$ ($c=-4.65$ m. sec.$^{-1}$). Origin of longitude lines is arbitrary. (a) Stream function computed frome quation (7). Isopleths are labeled in units of 10^5 m.^{2} sec.$^{-1}$ (b) Isobaric height pattern computed from equation (9). Isopleths are labeled in meters. (c) Isobaric height pattern from the linear inertial and Coriolis terms of equation (9). Isopleths are labeled in meters. (d) Isobaric height pattern from the nonlinear inertial terms of equation (9). Isopleths are labeled in meters.

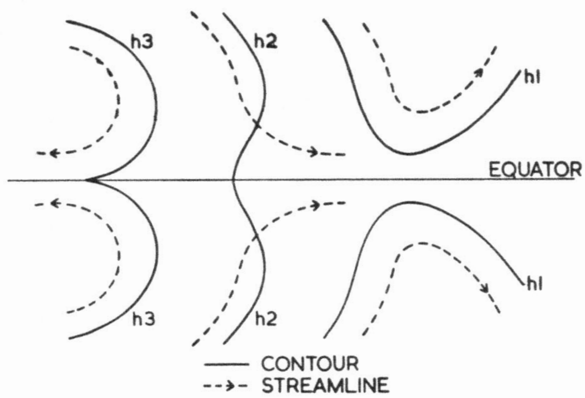

FIGURE 11.—Schematic representation of the "Diamond" pattern (after Johnson and Mörth [4]). Contours are solid lines, streamlines are dashed.

flow along the contours near the equator. Using particle dynamics, Vander Elst [9] concludes that "ducts" should produce cross-isobaric flow in the easterly current at low latitudes. Our results do not substantiate Vander Elst. We find the easterly flow to be very nearly parallel to the contours.

4. CONCLUSIONS

This investigation has shown that it is extremely difficult to devise pictorial models of the wind-pressure relationship in low latitudes even when we consider relatively simple inviscid, nondivergent flows. This was, perhaps, most strongly demonstrated in Case 4 in which quite different flow patterns were associated with more or less the same pressure pattern. Therefore, if we accept the philosophy that both wind and pressure reports should be employed if all possible information is to be obtained from the observations, and if the balance equation is to be the minimum acceptable pressure-wind relationship, it would seem that the low-latitude analysis problem is too difficult to be handled by subjective methods. Machine procedures, using techniques such as those proposed by Sasaki [7], would seem to be necessary. Indeed, this general approach to the tropical analysis problem is currently being employed at the National Meteorological Center, Suitland, Md.

During the course of this study, it was possible to generate equatorial pressure patterns which resembled some of the empirical pictorial models proposed by the East Africans. In particular, patterns similar to the "drift", "bridge", "diamond", and "duct" were generated. For the values of the parameters employed in our work, the flow pattern associated with the "drift" pressure pattern was quite different from that proposed by Johnson and Mörth [4]. On the other hand, the flow patterns associated with our "bridge", "diamond", and "duct" were similar to those proposed by Johnson and Mörth [4]. We have not studied the problem in sufficient detail to know whether similar results would be obtained if the various parameters entering the problem were varied.

Although the nonlinear terms in the vorticity equation are identically zero for the simple motions considered here (nondivergent perturbations with a single harmonic in the zonal and meridional directions superimposed upon a constant zonal current), the nonlinear terms in the primitive equations and in the divergence equation are significant in magnitude for the scales of motion and circulation intensities considered here. In some cases (for example, Case 1), the nonlinear inertial terms are an order of magnitude larger than the linear inertial terms and the Coriolis terms. Physically, this implies the unsurprising importance of centrifugal effects in the wind-pressure relationship at low latitudes. As a consequence, circulation centers close to the equator, clockwise and counterclockwise, tend to be associated with cells of low pressure.

Some of the generated pressure fields showed balanced, closed, high pressure cells centered on the equator. These Highs are cyclostrophically associated with saddle (hyperbolic) points in the flow pattern. The existence of such high pressure cells has been indicated to be dynamically impossible by some previous writers.

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